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Multibeam holographic formation of the polarization photonic structures in polymer-dispersed liquid crystals

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Abstract

The theoretical model of multibeam holographic formation of inhomogeneous polarization photonic structures in polymer-dispersed liquid crystals (PDLC) is developed in this work. According to obtained relations, numerical simulation of the spatial changing of the dielectric tensor is made.

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Keywords:

1. Introduction

Currently, polarization photonic structures (PPS) holographically formed in polymer-dispersed liquid crystals (PDLCs) by the polarization holography methods [1] are of great interest due to possibility to manage their optical properties dynamically [2]. Earlier [3] the theoretical model of holographic polarization gratings formation by two orthogonally polarized light beams in PDLCs has been developed with light-induced absorption changing taken into account. PPSs formation in PDLCs is possible due to the light-induced spatial inhomogeneity of the optical anisotropy of the material caused by the superposition of arbitrarily polarized recording beams on the sample plane, and stabilized as a result of phase separation of PDLC components during photopolymerization process. In the multibeam case, the phase difference between the interfering waves leads to a polarization state changing and also to an intensity modulation of the resulting field. The PPS' refractive index changing is caused not only by modulation of the material density, but also by the spatial distribution of the liquid crystal molecules orientation.

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Processes of multibeam holographic photonic structures formation in absorbent photopolymers were investigated in [4,5]. The purpose of this paper is to develop the theoretical model of holographic formation of the PDLC polarization photonic structures for the case of multibeam recording.

2. Theoretical model

We will consider the incidence of several flat coherent linearly polarized monochromatic light beams at the PDLC-air boundary (Fig. 1a). One of the beams we will take as the reference one. Remaining beams we will assume signal ones. Signal beams are orthogonally polarized with respect to the reference beam and their amplitudes are small, so we can neglect their interaction with each other.

In this case we can ignore the emerging intensity modulation and consider only the changes in polarization state of the total recording electromagnetic wave.

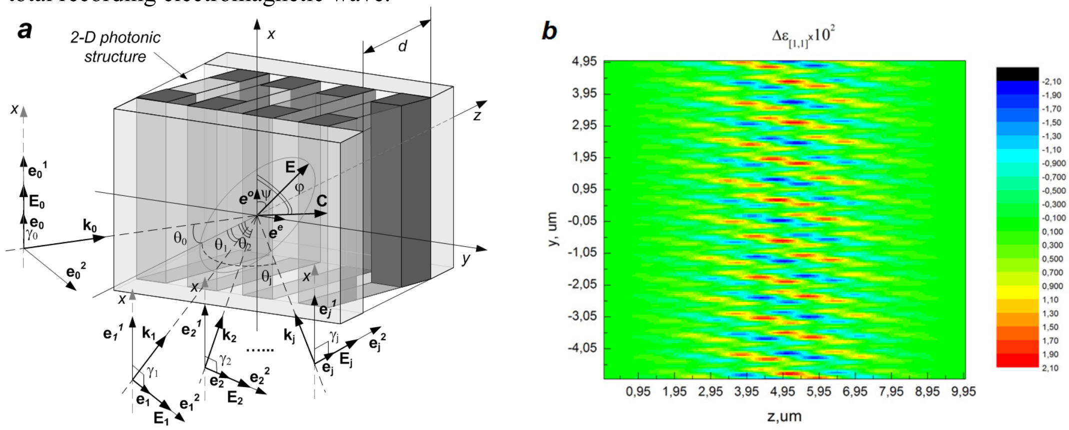

Fig. 1. (a) multibeam holographic formation of PPS, (b) results of numerical simulations.

On Fig. 1a we introduced following notations: $\mathbf{E}_j = A_j \cdot \mathbf{e}_j \cdot \exp\left[i\left(\omega \cdot t - \mathbf{k}_j \cdot \mathbf{r}\right)\right]$ – the electric field vectors of incident light beams; A_j – amplitudes of incident light waves; $\mathbf{e}_j = \dfrac{\mathbf{e}_j^1 + i \cdot \rho_j \cdot \mathbf{e}_j^2}{\sqrt{1+\rho_j^2}}$ – unit complex polarization vectors in the proper polarization bases; $\mathbf{e}_j^1, \mathbf{e}_j^2$ – orts of proper polarization bases; ρ_j – ellipticities of polarization ellipses; $\mathbf{r}$ – radius-vector; $j = 0\ldots N$ – beam number; N – the count of beams; θ_j, γ_j – incident and polarization angles; $\mathbf{k}_j$, – wave vectors of incident waves; $\mathbf{C}$ – liquid crystal (LC) director; d – sample thickness; $\mathbf{E}$ – the electric field vector of summary wave in the sample; $\psi(\mathbf{r})$ – angle of the summary wave polarization ellipse rotation; $\varphi(\mathbf{r})$ – angle of the LC director $\mathbf{C}$ rotation under the impact of light-induced Fredericks effect [6].

In the shown case there will be the “polarization” interference pattern in the sample, formed by the vector sum of all incident beams. The phase difference between the reference and each signal beam will cause the total wave polarization characteristics spatial changing, but not the intensity modulation (signal beams intensities are small).

Thus, in the sample several polarization diffraction gratings will be formed according to the mechanism described in [2, 3]. For a total optical field polarization characteristics changing description we will use the Jones' formalism to recording electromagnetic waves description as in [3].

$$J_j(\mathbf{r}) = M_j \cdot R_j \cdot D_j \cdot \exp\left[-\alpha\left(\mathbf{N}_j \cdot \mathbf{r}\right)\right] \cdot \exp\left[-i \cdot \mathbf{k}_j \cdot \mathbf{r}\right], \tag{1}$$

where $D_j = \begin{bmatrix} A_j^1 \cdot \exp\left[i \cdot \delta_j^1\right] \\ A_j^2 \cdot \exp\left[i \cdot \delta_j^2\right] \end{bmatrix}$ – Jones' vectors of polarized recording beams in the proper polarization bases [3], $A_j^{1,2}, \delta_j^{1,2}$ – amplitudes and phases of recording beams components, for linearly polarized light Jones' vectors will be $D_j = A_j^1 \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix}$; $R_j = \begin{bmatrix} \cos(\gamma_j) & -\sin(\gamma_j) \\ \sin(\gamma_j) & \cos(\gamma_j) \end{bmatrix}$, $M_j = \begin{bmatrix} 1 & 0 \\ 0 & \cos(\theta_j) \end{bmatrix}$ – matrices of the inverse coordinate axis rotation; $\alpha(\mathbf{N}_j \cdot \mathbf{r})$ – light-induced absorption coefficient changing [3].

Then each pair of "reference+signal" beams will form diffraction grating [3] by sum of their Jones vectors:

$$J_m(\mathbf{r}) = \sum_{j=0,m} J_j(\mathbf{r}), \tag{2}$$

where $m = 1\ldots(N\text{-}1)$ – number of grating.

To determine the polarization characteristics of each of the resulting waves we will introduce phazors:

$$\mu_m(\mathbf{r}) = J_m^e(\mathbf{r}) \Big/ J_m^o(\mathbf{r}), \tag{3}$$

where $J_m^o(\mathbf{r})$, $J_m^e(\mathbf{r})$ – summary Jones' vector components, corresponding to ordinary and extraordinary waves.

Then the spatial distributions of respective azimuths and ellipticities of each resulting waves can be determined by [3]:

$$\psi_m(\mathbf{r}) = \frac{1}{2} \cdot arctg\left(\frac{2 \cdot \mathrm{Re}\left[\mu_m(\mathbf{r})\right]}{1 - \left|\mu_m(\mathbf{r})\right|^2} \right), \quad \rho_m(\mathbf{r})^2 = \frac{1 - \left[1 + 4 \cdot \mathrm{Im}^2\, \mu_m(\mathbf{r}) \Big/ \left(1 - \left|\mu_m(\mathbf{r})\right|^2\right)^2 \right]^{0.5}}{1 + \left[1 + 4 \cdot \mathrm{Im}^2\, \mu_m(\mathbf{r}) \Big/ \left(1 - \left|\mu_m(\mathbf{r})\right|^2\right)^2 \right]^{0.5}}. \tag{4}$$

Director rotation angles spatial distributions $\varphi_m(\mathbf{r})$ as in [3] we will determine by solving the energy balance equation [7] with the spatial distribution of electric field of recording beam taken into consideration:

$$\int_0^{\varphi_m} \left[\sin^2 \psi(\mathbf{r}) - \sin^2 \varphi'\right]^{-1/2} d\varphi' = \frac{1}{\xi_m(\mathbf{r})} \cdot \left(\frac{d}{2} \pm z \right), \tag{5}$$

where $\xi_m(\mathbf{r}) = \left[\frac{K_{33} \cdot 8\pi}{\varepsilon_e - \varepsilon_o} \cdot \frac{1}{\left[E_m^o(\mathbf{r})\right]^2 + \left[E_m^e(\mathbf{r})\right]^2} \right]$ – spatial distribution of the electric coherence length, ε_o, ε_e – components of unperturbed dielectric tensor (ordinary and extraordinary); K_{33} – Frank's elasticity coefficient; $E_m^o(\mathbf{r})$, $E_m^e(\mathbf{r})$ – spatial distributions of electric field vectors (ordinary and extraordinary) [3].

In the conditions of the strong coupling of the liquid crystal molecules with boundary surfaces and big rotation angles, the equation (5) can be solved numerically as a sum of two cases: increasing (+*z*) and decreasing (-*z*) rotation angles. Also, the photo-induced absorption coefficient changing [3] must be taken into account.

Then, orientation of liquid crystal director can be written as:

$$\mathbf{C}_m(\mathbf{r}) = \begin{bmatrix} \sin\varphi_m(\mathbf{r}) \\ \cos\varphi_m(\mathbf{r}) \\ \sin\varphi_m(\mathbf{r}) \cdot \sin((\theta_0 - \theta_{m+1})/2) \end{bmatrix}. \tag{6}$$

Then perturbation of the dielectric tensor of the sample, caused by the formation of each grating will be [3]:

$$\Delta\boldsymbol{\varepsilon}_m(\mathbf{r}) = (\varepsilon_e - \varepsilon_o)[\mathbf{C}_m(\mathbf{r})\mathbf{C}_m(\mathbf{r})] . \tag{7}$$

We will represent each perturbation as Fourier series of spatial harmonics:

$$\Delta\boldsymbol{\varepsilon}_m(\mathbf{r}) = \sum_{i=0}^{M} \Delta\boldsymbol{\varepsilon}(\mathbf{r})_m^i \cos(\mathbf{K}_i \cdot \mathbf{r}) \; ; \; \Delta\boldsymbol{\varepsilon}(\mathbf{r})_m^i = \frac{1}{2\pi} \int_{-\pi}^{\pi} \Delta\boldsymbol{\varepsilon}_m(\mathbf{r}) \cos(\mathbf{K}_i \cdot \mathbf{r}) d(\mathbf{K}_i \cdot \mathbf{r}) \tag{8}$$

where $\mathbf{K}_i = i \cdot \mathbf{K}$, $\Delta\boldsymbol{\varepsilon}(\mathbf{r})_m^i$ – gratings vectors and harmonics amplitudes.

The total perturbation of dielectric tensor can be written as a sum of each perturbation because of their smallness. Earlier [8] it has been shown that the main contribution to the dielectric tensor changing makes second spatial harmonic $\Delta\boldsymbol{\varepsilon}(\mathbf{r})_m^2$. Thus, the total perturbation can be written as:

$$\Delta\boldsymbol{\varepsilon}(\mathbf{r}) = \sum_{m=1}^{N-1} \Delta\boldsymbol{\varepsilon}(\mathbf{r})_m^2 \cos(\mathbf{K}_2 \cdot \mathbf{r}) . \tag{9}$$

3. Numerical simulations

On Fig. 1b numerically calculated changing (9) of the $\Delta\boldsymbol{\varepsilon}(\mathbf{r})_{1,1}$ element of sample dielectric tensor, caused by three multiplexed by angle polarization diffraction gratings formation are shown. We used the following model parameters: $\lambda = 633$ nm; $\theta_0 = \pi/6$, $\theta_j = \theta_0 + j \cdot \pi/6$; $\gamma_0 = 0$, $\gamma_j = \gamma_0 + \pi/2$; $d = 10$ um; $n_o = 1{,}535$; $n_e = 1{,}68$; $A_j / A_0 = (N-1)^{-1}$; $N = 4$.

As can be seen from Fig. 1b, the inhomogeneous 2-D polarization photonic structure is formed in the sample. The inhomogeneity of recorded structure caused by boundary conditions, photo-induced absorption coefficient changing and formation of angularly multiplexed polarization gratings.

Conclusion

Thus, the possibility to form complicated polarization photonic structures (superimposed polarization gratings by angle multiplexing) in the PDLC samples by methods of polarization holography is shown. Obtained results for the sample dielectric tensor perturbation can be used to develop a model of light beams diffraction on this structures using the coupled-wave theory.

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References

[1] Sh. D. Kakichashvili, Soviet Phusics Uspekhi. 4(1978) 681-683.
[2] G. M. Zharkova et al., Liquid Crystals and their practical use. 1(2011) 36-42.
[3] A.O.Semkin, S.N. Sharangovich, Proceedings of APCOM 2014. p. 9.
[4] S.N. Sharangovich et al., SPIE Proc. Vol. 5636 (2005) 802-811.
[5] E.A. Dovolnov, S.N. Sharangovich, Optics and Spectroscopy. Vol. 105, 2(2008) 310-319.
[6] B.Ya. Zel'dovich, N.V. Tabiryan Sov. Phys. JETP. 4(1982) p. 656.
[7] A.S. Sonin, Vvedenie v fiziku zhidkih kristallov, M.: Nauka, 1983.
[8] A.O.Semkin, S.N. Sharangovich, Electronnye sredstva i sistemy upravleniya: proceedings of 10th international conference 2014. Part 1. P.180.